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PHASE AND STRUCTURAL VARIATIONS IN TITANIUM UNDER TRANSIENT LOADS

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Translation of "Fazovyye i strukturnyye izmeneniya v titane pri impul'sivnykh nagruzkakh," Novyy konstruktsionnyy material -- Titan (A New Construction Material -- Titanium), Edited by I. I. Kornilov and N. G. Boriskina, Moscow, "Nauka" Press, 1972, pp. 70-73

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16. Abstract

Research into phase and structural variations in titanium under transient loads showed that there was a phase transition under pressure, similar to that of the α-ω phase transition during static loading. A method was developed to fix the high-temperature phase in pure titanium by freezing in liquid nitrogen and applying dynamic pressure. This can also be used for studying high-temperature phases of other pure metals.

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PHASE AND STRUCTURAL VARIATIONS IN TITANIUM UNDER TRANSIENT LOADS

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Several authors have investigated the phase transitions in titanium in temperature ranges from room temperature to 1000°, and in static pressures from 20 to 160 kbar [1], and the existence of three solid phases of titanium has been established. In the temperature range to 840° and pressures from 90 to 160 kbar, an ω-phase was detected, the so-called Jameson phase, which is a modification with a distorted body-centered cubic lattice. The type of lattice is determined by X-ray diffraction analysis after cooling a sample to room temperature and reducing the pressure to normal, since warming at normal pressure to a temperature of 110° causes the complete opposite transition into the α-phase (a hexagonal close-packed lattice). A similar phase diagram in a temperature-pressure coordinate also exists for iron, and in research both static and dynamic loading with high pressure was used [2, 3, 4, 5]. The aim of the present work was to investigate the phase and structural variations in titanium during dynamic (impact) loading. /70*

Specimens from VT1-1 titanium, measuring 25 x 25 x 20 mm were pressed into a lead container until they disintegrated (Fig. 1). Pressure was created when a steel plate 2 to 8 mm in thickness was cast when two types of explosives were detonated. The conditions for conducting the experiments are shown below; the pressure, obtained when the plates impacted, was determined by a method suggested in work [6].

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* Numbers in the margin indicate pagination in the foreign text.

Type of explosive	6ZhB ammonite			Trotyl					
Pressure, kbar	30	60	90	90	90	120	150	180	200
Height of charge, mm	10	20	35	25	40	12	15	20	22
Thickness of plate, mm	2	2	2	6	8	2	2	2	2

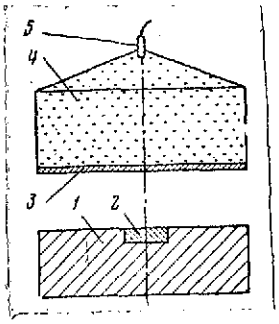

Fig. 1. A diagram of the experiment: 1. lead container; 2. specimen; 3. plate; 4. explosive; 5. electric detonator.

After loading, the amount of residual strain on the specimens, the hardness on the impact surface, according to thickness, was measured, and metallographic and X-ray diffraction analysis was conducted.

The presence of a phase transition in titanium at a pressure from 90 kbar and above is confirmed by the following data.

1. The dependence curve of the relative residual strain on the applied pressure bends at a pressure of 90 kbar. As the pressure is increased, the amount of residual strain is unchanged (Fig. 2, curve 1).

2. The dependence curve of the hardness on the impact surface on the amount of pressure has an inflection point at a pressure of 90 kbar (Fig. 2, curves 2, 3).

3. Irrespective of the initial hardness of titanium, hardening at a pressure of 90 kbar reaches one and the same value, and when there is an increased pressure, varies identically, as shown below. /71

Pressure, kbar	30	60	90	120	150	180	200
Hardness after loading, kg force/mm^2							
Initial 220	224	230	236	244	274	283	296
Initial 150	—	185	236	245	275	—	290

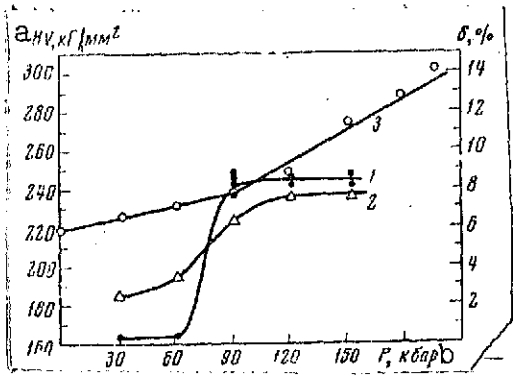

Fig. 2. The dependence on the relative residual strain and hardness on the impact surface of titanium on pressure applied: 1. the relative residual strain; 2. hardness on the impact surface; 3. the same, specimens, cooled in liquid nitrogen, before impact.

Key: a. HV, kg force/mm^2; b. P, kbar

4. As a result of metallographic analysis, it was determined that when a pressure of from 90 kbar and above is applied, the overwhelming majority of grains have a martensitic formation (Fig. 3).

No change of phase composition was determined by X-ray diffraction analysis. As was shown in work [1], the rapid cooling of a specimen with subsequent reduction of pressure, made it possible to fix a high pressure phase. It must also be noted that high-temperature phases in pure titanium and iron, as in other metals, with a temperature phase transition, can be fixed at room temperature, in spite of being able to achieve a rate of cooling from the range of existing high-temperature modifications to 10^4-10^5 degrees/sec [7]. Specimens, during impact loading, are heated to a temperature of 150-250°, depending on the pressure applied. A method was developed, making it possible to obtain a mean temperature of the specimen during the loading process lower than room temperature, to reduce the temperature quickly. Before impact loading, specimens were cooled to the temperature of liquid nitrogen, directly before loading, the temperature of specimens did not exceed -170°. The remaining conditions for conducting experiments and results obtained are similar to those shown above, with the exception of information from X-ray diffraction analysis.

Fig. 3. Microstructure of titanium, x 150. a. Initial specimen; b. specimen hardened by a pressure of 200 kbar.

X-ray diffraction analysis was conducted on URS-60 equipment, in an X-ray diffraction chamber with conditions: current intensity 10 mA, voltage 22 kV, exposure time, 16 hours. Photography was done on the specimen surface affected by the shock wave. At a pressure of 90 kbar, caused by casting a plate 8 mm thick, and 180 kbar, by casting a plate 2 mm thick, β-phase of titanium was seen on the surface of a congealed specimen at a depth of approximately 0.3 mm; no change in the phase composition was seen in the remaining cross section of the specimen.

Below is a comparison of the interplanar distances of a phase, obtained from the experiment, with those from literature [8], showing the coincidence of interplanar distances, which makes it possible to determine reliably the generating phase as the β-phase.

Interplanar distances:

Experimental data	2,341	1,620	1,411	1,208	1,028	0,944	0,877
Tabulated values for β-titanium [8]	2,31	1,64	1,33	1,16	1,03	0,943	0,875

Consequently, the experiments carried out with impact loading /72 of titanium specimens determined the presence of an opposite phase

transition, similar to the transition of the α-phase to the ω-phase, investigated during static loading with high pressure. Moreover, it was possible to fix the high-temperature β-phase at room temperature on cooled specimens.

On the basis of research conducted, it can be assumed that there is a subsequent, more probable mechanism for the observed formation and fixing of the β-phase in titanium.

1. A thin layer (up to 0.3 mm) on the specimen surface during impact has an increased thermal pressure due to: a) thermal pressure during strain; b) heat from the unavoidable plastic strain of this layer during impact (the crumpling of roughnesses, and the fact that the surfaces do not come into contact simultaneously).

2. During pressure, there is a formation of a high-temperature β-phase, and not a low-temperature ω-phase in the shock wave higher than required for the phase transition in the thin surface layer.

3. In normal conditions (without cooling), this phase transition is reversible, and the high-temperature phase is not maintained after pressure is removed. Defects occur in the structure, linked with reversible transformation, by nature identical to defects from cold hardening. Residual defects in this case are of a complex origin: a) on account of the compressibility of the substance (for example, according to the Smith system [9]); b) owing to the plastic strain of the upper layer; c) due to phase transition. The formation of defects is accompanied by a less complex picture of their annihilation, due to the increase of temperature.

4. Loading by shock waves of the same pressures allows a high-temperature phase to be maintained on congealed specimens and makes the phase transition irreversible. This occurs mainly /73

due to the following phenomena: a) the difficulty of the annihilation of defects, forming boundaries of crystals of the high-temperature phase (without annihilation or removal of defects, crystals of the formation phase cannot disappear); b) the reduction in energy of the lattice and the weakening of the thermal motion of atoms in a congealed metal, which increases the stability of the phase transition; c) a distinct hardening of the surface layer due to an increased and faster removal of heat from it into the colder internal layers.

It is also possible that the pressure applied also has a direct effect on the kinetics and conditions of phase transition. In work [7] it was found that the formation of a martensitic structure in iron when hydrostatic pressure was applied (40 kbar), occurred at a rate of cooling of 100°/sec, instead of 10^5 degrees/sec, required for hardening when there is no pressure. In our experiments, the rate of cooling in this thin layer is 10^7-10^9 degrees/sec.

Conclusions

1. It was found there was a phase transition when dynamic pressure was applied, similar to the phase transition ($\alpha \rightarrow \omega$), brought about during static loading.

2. A method was developed for fixing the high-temperature phase in pure titanium by preliminary freezing in liquid nitrogen and applying dynamic pressure, using intensive shock waves.

3. It is possible that there is a mechanism for the observed formation and fixing of the β-phase in titanium.

4. The described method of fixing can be used for studying high-temperature phases of other pure metals.

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